

Review

Drainage in railways

Roberto Sañudo^{a,*}, Marina Miranda^b, Carlos García^c, David García-Sánchez^d^a Transport, Projects and Processes Technology, Department Railways area, E.T.S.I. Caminos, Canales y Puertos, University of Cantabria, Avda. de Los Castros, 44, 39005 Santander, Cantabria, Spain^b Group of Geotechnical Engineering, Department of Ground Engineering, and Materials Science, E.T.S.I. Caminos, Canales y Puertos, University of Cantabria, Avda. de Los Castros, 44, 39005 Santander, Cantabria, Spain^c Department of Sciences and Techniques of the Water and the Environment, E.T.S.I. Caminos, Canales y Puertos, University of Cantabria, Avda. de Los Castros, 44, 39005 Santander, Cantabria, Spain^d TECNALIA Research and Innovation, Parque Tecnológico de Bizkaia, Astondo Bidea, Edificio 700, E-48160 Derio, Bizkaia, Spain

HIGHLIGHTS

- Review of different design and modelling methods for track drainage in railways.
- Classification of drainage systems in railways.
- Construction description techniques.
- Highlights and recommendations to choose the best system.
- Adaptation and resilience in drainage. A new design tool.

ARTICLE INFO

Article history:

Received 31 August 2018

Received in revised form 1 February 2019

Accepted 11 March 2019

Available online 28 March 2019

Keywords:

Railways

Drainage

Drainage resilience

Drainage construction

Drainage recommendations

ABSTRACT

The effect of water must be considered during the different phases of the life cycle of infrastructures. When it is not properly managed, it can generate problems that may lead to infrastructure closure or even destruction. This paper presents a review of the different drainage systems existent in railway infrastructures. Current design criteria have become obsolete in many cases due to effects of climate change. Therefore, the purpose of this article is to serve as a starting point for new designs. To offer measures to address this problem and increase the resilience of the structures by means of a new design tool.

© 2019 Elsevier Ltd. All rights reserved.

Contents

1. Introduction	392
2. Railway infrastructures	392
2.1. Conventional ballast track	393
2.2. Slab track, ballastless track	393
3. Inefficacy of drainage systems on the different elements of the railway infrastructure	394
3.1. Risk and damages on railway platform infrastructure	394
3.2. Risks and damage on railway platform superstructure	395
3.2.1. On the rails	395
3.2.2. Fastening elements	395
3.2.3. Sleepers	395
3.2.4. Structures	395

* Corresponding author.

E-mail addresses: roberto.sanudo@unican.es (R. Sañudo), marina.miranda@unican.es (M. Miranda), carlos.garciateran@unican.es (C. García), david.garciasanchez@tecnalia.com (D. García-Sánchez).

3.2.5.	Ballast	396
3.2.6.	Ballast, hydraulic properties	396
3.2.7.	Concrete slab	396
3.3.	Traffic, operations and circulation risk	397
3.4.	Damage on drainage system	397
3.5.	Damage to a third parties	397
4.	Drainages systems in linear projects	397
4.1.	Drainage in infrastructures	397
4.2.	Classification of drainage systems in railways	398
5.	Design and calculation	399
5.1.	Calculation of design flow	399
5.2.	Sizing of drainage elements in general	399
6.	Construction	400
6.1.	Examples of drainage works in railways	400
6.2.	The use of drainage materials	405
6.3.	Recommendations and guidelines about railways drainage	405
7.	Adaptation and resilience in railway drainage	406
7.1.	Drainage design flowchart	410
8.	Conclusions	411
	Conflict of interest	411
	Acknowledgments	411
	References	412

1. Introduction

This study and analysis of the drainage systems in the railway track has been motivated by the existence of several problems on European railways originated by Extreme rainfalls and floods. According to recent studies, and considering the European Union guidelines, it is expected that this type of events will increase both, its frequency and its severity because of Climate Change.

An overview of the problems generated by drainage inefficiency risk in civil engineering structures, together with a brief description of the different systems used in railway infrastructures around the world, are presented in this first point.

Water can cause innumerable problems in civil works that can lead to the decommissioning of railway assets. Some of them are related with soil behaviour and others are directly linked to the structure materials itself. Soil strength and stiffness can be reduced generating greater short term and long-term settlements. In addition, the soil can increase its volume due to frosting of interstitial water, and it can even potentially reach liquefaction. Metallic materials can get corroded and reduce its performance, hence reducing safety.

Specifically, main risks on railway infrastructures are related with loss of geometric track quality. This generally occurs due to differential settlements on the platform. Some of the causes can be [1]: erosion due to surface water and frost, contamination of ballast by capillarity and speeding up the weariness of granular material.

These causes may generate problems on the infrastructure, moving material and operations which are presented more in depth in Section 3 of this paper.

It is important to notice that 92% of stability problems in French railway network have been related to insufficient drainage of the platforms [2]. In addition, between 2007 and 2014, Network rail in the UK paid nearly £10 million to operators because of railway disruptions caused by flooding. 45% of these disruptions were attributed to poor drainage systems [3]. Only in the UK in the last 5 years Network Rail have had to compensate rail operators in excess of £74 million for delay minutes caused by flooding [4].

Once an overview of the most common problems due to poor drainage efficiency in civil engineering structures have been presented, the two most important types of railway structures are shown in Section 2. Section 3 describes the problems in the railway infrastructures caused by an inadequate drainage network. Section 4 outlines the drainage systems in the infrastructures. Section 5 gives a summary of the most used calculation modes. Different designs used in the railways are analysed in Section 6. Features of several regulations around the world are also presented there. Finally, Section 7 explains the importance of the drainage network in the future and introduces the concept of resilience. Besides, several examples of action policies carried out in pioneer countries in these initiatives are provided. The article ends with a new design tool for drainage elements providing recommendations on design and conservation of drainage systems in railway infrastructures as a result of the study carried out.

2. Railway infrastructures

Railway infrastructures have developed to respond to the demanding conditions required on railways nowadays in terms of: loads, geometries and levels of comfort. For this reason, geo-

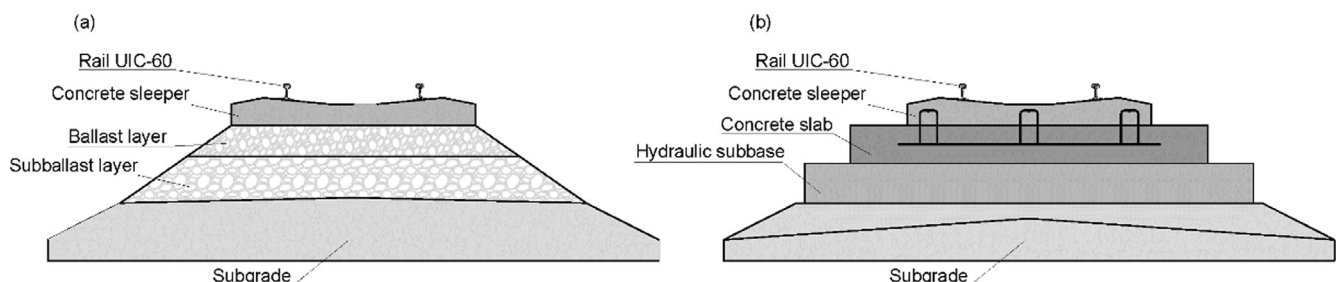


Fig. 1. Ballast track system scheme a), slab track system scheme b).

Table 1

Classification of different slab track systems.

Slab Track Systems					
Discrete Rail Support				Continuous Rail Support	
With sleepers or blocks		Without sleepers			
Sleepers or blocks embedded in concrete	Sleepers on top of asphalt concrete roadbed	Prefabricated concrete slabs	Monolithic in situ slabs (on civil structures)	Embedded rail	Clamped and continuously supported rail
Rheda		Shinkansen	Paved-in-track		Cocon
Rheda 2000	ATD	Bögl	Green-track	Paved-in-track	Track
Rheda-Berlin	BTD		Hochtief	Light rail Road	ERL
Züblin	Getrac		On civil structures	Crossing Deck	Vanguard
LVT	Sato		FFC	Track	KES
Heitkamp	Walter		BES BTE-BWG/WBG	Ortec	Edilon
SBV			BTE-Hilti	Saargummi	

Table 2

Risks caused by water depending on the type of rail track systems.

Rail Track System	Ballast track	Slab track
Risks and Damages		
Infrastructure damages	Fill settlements/mbankment settlement Slope instability/failure of embankment Superficial erosion on slopes Platform bearing capacity reduction	
Superstructure damages	Granular layers pollution Ballast pockets Internal erosion of granular materials Layers separation: ballast and sub ballast Affection to superstructure elements Rail, fastenings, sleepers, ballast	Superficial cracks Exposure of armour Slab integrity damage Bottom support erosion (sleepers) Affection to superstructure elements Rail, fastenings, supports, slab
Operations and circulation risks	loss of geometric track quality Loss of conform and security during circulation Circulation interruption (delays) Signalling problems Loss of power to the soil. Current leakage Erosion and undermining due to a poor design	
Drainage network damages	Silting of drainage system	
Third parties damages	Silting and malfunctioning Nearby residential and industrial areas affection Problems caused by current leakage on nearby conduits. Human and material losses and damages	

metric tolerances, resistance and the service life of materials have had to be improved. Traditional track, ballast track, is still suitable and allows these advances in the railway system. However, more than half a century ago, another system appeared where a binder material replaces ballast. This binder material is usually concrete or bituminous agglomerate. This modern system, slab track, is still under development today and it is the subject of numerous investigations e. g. [5–7]. There are endless references about the different types of slab track, its comparison with the ballast track and its advantages and disadvantages [6,7]. Two of the most important differences between both systems are the construction and maintenance costs. While construction costs of ballast track are lower than those of the slab track, maintenance costs of slab track are lower than those of the ballast track [8]. A thorough review and comparison of both track systems, is beyond the scope of the paper. It just identifies the typological differences between one system and another, and presents their corresponding drainage systems.

As shown in Fig. 1, the differences are mainly present in the materials and their behavior against runoff and filtration. In ballast track, ballast is a highly porous material and therefore a draining

one. This indicates that attention should be given to the water that reach the waterproof lower layers. To evacuate it, a certain degree of compaction and inclination to the layer is given (in Spain variable between 3 and 5% depending on the type of track). In slab track, water filtration depends on concrete porosity. Therefore, it is enough to use non-porous concretes and give a certain inclination on the surface (concrete slab).

2.1. Conventional ballast track

The structure of a conventional ballast track consists of several elements (Fig. 1a) e. g. the rail, the fasteners, the sleepers, the ballast, the sub-ballast and lower layers (normally shape layer and sub-base). The typology of the drainage system varies depending on the type of soil and track; and of course, the climatic conditions in each zone.

2.2. Slab track, ballastless track

A concrete or bituminous agglomerate slab replaces ballast on slab track systems (Fig. 1b). The other substructure elements are

maintained or slightly changed. The rail can be directly placed on the slab (without sleepers), or on elastic elements (sleepers with fasteners). Constructive requirements are generally more demanding on slab track than on the ballast track systems. Most important restriction is the absence of settlements on the platform [6].

A summary of most important slab track systems is provided by [5]. There are several classifications of slab tracks [1]. The simplest classification, which encompasses all existing track systems, is the one based on the type of supports [1]. It divides the types of slab track into two groups: (i) discrete support systems, in which the rail is supported on discrete support elements such as sleepers or other support elements. And (ii) continuous systems, those in which the rail is supported continuously throughout its entire length. Table 1 shows an example of this classification [6,7].

Drainage systems on slab track depends on the type of slab track system employed. Permeability greatly depends on the degree of porosity of the binder material used (concrete or bituminous agglomerate).

3. Inefficacy of drainage systems on the different elements of the railway infrastructure

In railway structures, problems generated by the ineffectiveness of drainage systems can be grouped into five large groups. They are presented in Table 2, and described in greater depth later. It is worth nothing, that the types of damage depend on the type of railway structure involved: traditional ballast track or slab track.

There are risks within the railway environment and risks outside the railway environment. Therefore, in the same way there is a distinction between damages on the environment and outside the railway environment. Damages in the environment can be

divided into those caused on the superstructure, those caused on the infrastructure and those caused to the circulation and operations. Risks and or damages on the drainage network are within the latest. Risks or damages outside the railway environment can be basically divided in two types: damages to the drainage network, but outside the railway structure, and damages to third parties or conditions in the vicinity. All of them are described in more depth below.

3.1. Risk and damages on railway platform infrastructure

Damages associated with the infrastructure are similar for both types of tracks since, as previously stated, this part of the structure is analogous in the two cases. Track substructure problems are frequently due to water remaining in the substructure for long periods. For example, higher rates and magnitudes of deformations, higher plastic strain, lower shear strength, lower resilient modulus and higher plastic strain can be generated due to excessive moisture in the track structure. In [9–11] we can find a relationship between the moisture content and the resilient modulus showing its reduction when increasing water content. This is more visible when ballast is fouled. Other risks are the increase of slopes instability or appearance of superficial erosions. They can be produced by water filtration or prolonged presence of water, as well as, the problems related with material dragging such as piping. It depends on particle size and water velocity mainly. Lane 1953 [12], based on experimental work, developed a chart showing minimum speed needed to move particles depending on its diameter. In addition, it is important to highlight the problems generated by water freezing when temperatures are close and lower than zero degrees Celsius. The main one is known as freeze heave, which hardly appears in



Fig. 2. Expansion joint lubricated due to iron oxide in the rail foot, rail head and the contact with the fastenings.

clean ballast, but is more common in fouled ballast [13] and in slab track. Latvala et al. [14] reported that problems due to freeze and thaw cycles are mainly related with bad drainage conditions. Finally, feature potential problems generated by liquefaction, although they are not common rail track structures.

Subgrade deformations can generate, in traditional track systems, ballast pockets. These can be filled with water and can lead to softening of surrounding areas generating problems of track geometry and resistance. Depending on their magnitude, their correction is made by using subsurface ballast drains at the deepest point of the pocket, or by improvement of the embankment. Providing drainage to the ballast pocket, by cross drains can reduce the softening generated by the water. Improvement of the embankment is the most employed solution.

Usually the platform has a low permeability. This makes it difficult for the water to cross it, so water will runoff. Therefore, it needs to be provided with a certain slope and a good compaction to avoid problems of water accumulation, as presented below.

Ground water is a vital factor in slope stability. Water must be channeled to storm water drains or natural water courses. Bonnett [15] give us two geotechnical classical approaches, short term considerations and long-term considerations. The ground water affects differently in both cases.

3.2. Risks and damage on railway platform superstructure

The superstructure on both types of tracks is different. Therefore, the damages or risks due to non-evacuated water may differ. This is mainly due to the different nature of the ballast and the concrete or bituminous material used. However, there are similar elements in both cases hence in these cases damages will be similar. In the following, most important risks and damages are described.

3.2.1. On the rails

Inside tunnels, corrosion of rails is stronger than outdoors because of higher humidity rates. Rail corrosion may lead to loss of net or effective resistant section in the rail. Therefore, to the reduction of rail life cycle. This corrosion can be increased by insufficient ventilation of the tunnel, smoke from diesel and old steam trains, stray currents on electric traction, and several electrochemical processes taking place in the contact surface between fixing elements (rail foot) specially. Heavily corroded rail sections need

to be controlled permanently because of risk of failure. In general, rails placed inside humid tunnels have a life cycle of half the life of rails outside under favorable conditions. One of the commonly accepted preventive interventions or mitigation actions is the installation of cathode protections.

In the expansion joints also, problems appear and need to be lubricated all time. The oxidized iron in the rails in these areas can make it difficult to slip and perform a correct expansion. If there is no a free expansion of the rail, stresses, dangerous for the structural integrity of the rail, may appear (see Figs. 2 and 3).

3.2.2. Fastening elements

As a result of humidity (specifically in tunnels) elements of the structure are under highly corrosive conditions. This increases their weariness (see Fig. 4). This is because humidity gets into superficial cracks. To prevent this, it is advisable to: (i) reduce the use of joints in tunnels. Therefore, welded rail is employed. (ii) not to use bearing plates between rail and sleeper depending on its material.

3.2.3. Sleepers

It depends on sleeper's material. In general, for reinforced concrete sleepers water influence is low and it only influences on the reinforcement if it is in direct contact with the water. Even if timber is thought to be not a good material, it can be employed. In some cases, as for example for juniper wood, humidity does not have unfavorable effects. It is not advisable to use mix sleepers and steel ones due to risk of premature corrosion in humid areas.

3.2.4. Structures

Any structure made of metal elements is subjected to water effect. As it is known, water oxidizes metallic structures, causing a deterioration that increases over time. Therefore, it is necessary to evacuate water quickly and efficiently. The simplest way to do it is by gravity. However, this evacuation must be conducted efficiently so as not to cause other problems in other parts of the structures (foundations or its bases).

In tunnels, water can also be evacuated by gravity, by generating inclination in the floor, but additionally, some factors have to be avoided. E.g. A continuous water flow on the catenary or the drip, capable of forming stalactites that could touch the catenary. Dripping on the support thread, since corrosion can cause the



Fig. 3. Sleepers, rails and joints affected by wet conditions.



Fig. 4. Wooden sleeper, iron base plate and screw spike affected by wet conditions.

breakage of the hangers with the consequent danger of snagging. These can be done through deflecting elements that divert water to the nearest conduits by the shortest path.

3.2.5. Ballast

In traditional rail track systems, ballast is a main component of the structure. One of its main functions is to contribute to evacuate water. Ballast is a granular material and it can evacuate water on the superstructure due its high hydraulic conductivity. It is a fundamental part of the drainage system. However, subgrade material and slope are important for superstructure drainage too. If the subgrade is form by clayed soil, water does not go through it and it may contaminate ballast by introducing clay particles into the granular material [8,16,17,18]. This reduces ballast performance. It reduces its capability to absorb dynamic loads and reduces the ability to evacuate water. This phenomenon generates fouled ballast and it is also known as mud pumping [19]. In tunnels, water effect on the ballast has another factor added to the previous one. Residues, particles and materials dragged by the seepage within the tunnel stay on the ballast contaminating it.

There are two main causes of ballast fouling, degradation of the material itself due to the cyclic loads and infiltration or inclusion of fine particles from the exterior [20]. Dynamic loading of the railway track leads to ballast particle breakage. Around 70–76% of fines generated are form ballast breakage [18,21]. Ballast fouling reduces its permeability, which is fundamental in the drainage system of railways structures. Therefore, it is important to quantify ballast-fouling degree to find an acceptable limit before maintenance works are needed. These fouling indicators can be divided in two groups: the ones mass-based measures, and the indicators based on inherent properties. Some examples of the first ones are the percentage of fouling and the fouling index proposed by [18]. It was modified by [22] They changed it to meet the Australian Rail Track conditions. These mass based indicators can give inaccurate fouling rates when particle unit weight of fouling materials have different specific gravity [21]. Therefore, property inherent based indicators were developed. One example is the percentage of void contamination (PVC) proposed by [23]. The void contamination index (VCI) was defined by [21].

There are several methods to maintain ballast clean varying in cost, effectiveness and requirements needed. Most common ones are: track undercutting, shoulder cleaning and, track vacuuming. The latest has a slow rate progress and therefore it is just used for small areas. The other two are mechanized and have higher production rate. Selig et al. [24] provided information about the drainage capacities of ballast according to the different ballast cleaning approaches. When ballast is completely fouled the rainfall

rate that saturates the ballast at the track center is 0.127 cm/hour. After partial depth undercutting this rainfall rate increased until 0.762 cm per hour. When shoulder cleaning takes place the rate increments to 3.56 cm per hour. And when the full depth of ballast is cleaned the estimated flow rate to get saturation on the central part is 15.24 cm per hour. This high increment is due to the shortening of the drainage path. Brazilian railways are very old, they are privatized, and they are hardly subjected to substitution or ballast improvement work [25].

3.2.6. Ballast, hydraulic properties

Characteristics of clean ballast material vary widely but it is commonly a uniform coarse material with particle sizes between 10 and 63 mm and a coefficient of uniformity (Cu) varying between 1.5 and 3 [21]. Ballast uniformity is required as it is better for drainage purposes and hydraulic conductivity of ballast is a key factor on the design and performance of drainage system in railway structures, as shown before.

Generally hydraulic conductivity of clean ballast is around 0.3 m/s, but it decreases in fouled ballast. Permeability of less than 10^{-4} m/s is considered unacceptable for ballast [18,21].

The suggested limited value of ballast hydraulic permeability in design is around 10^{-3} m/s, which correspond to a fouling index of about 15 [1]. Therefore, it is important to quantify the degree of fouling to be able to fix the limits before maintenance is needed. As Ballast permeability is a key factor on track drainage design it has been studied by many authors. Several studies have been performed to find the effect of ballast fouling on the hydraulic conductivity of ballast under saturated conditions [20,25–30]. Danquan et al. 2014 [28] performed large scale permeability tests of clean and fouled ballast with limestone, kaolin and ballast. For a relative ballast fouling ratio of less than 10% the hydraulic conductivity does not depend on the fouling material. However, for values higher than 10% fouling material properties affect hydraulic conductivity. For a relative ballast fouling ratio of 35% the hydraulic conductivity tends to be similar to the one of the fouling materials. They found that the breaking point when drainage become impeded by fouling is 25% of relative ballast fouling ratio. Sussmann et al. 2012 [20] performed a similar study and found the breaking point at 30% of fouling index. Other studies such as [31], have developed new equipment to test the hydraulic conductivity under unsaturated conditions.

3.2.7. Concrete slab

Slab track is usually built with a slab of reinforced concrete or bituminous concrete. In general, concrete is not very porous, so it does not let the water pass through it. The reinforcement should



Fig. 5. Ballast track collapse due to floods.

not be in contact with the air, so a minimum covering is usually placed to reduce the risk of oxidation. In some countries, such as the United States, that armour is coated with an epoxy-based paint system to prevent any cathodic reaction. Damages that water generates in this part of the superstructure are indirect and are related to the settlements and movements of the lower layers. They can generate cracks, causing even the fracture of the plate. On the contrary, a direct risk is the possible creation of superficial imperfections, and oxidation of the reinforcement. The armour increases in volume and may create cracks or cause the breakage of the concrete. It is important to point out as well the potential chemical attack to the concrete or material that forms the plate.

3.3. Traffic, operations and circulation risk

It is worth nothing that contact between metallic material and electrolyte needs to take place for the corrosion reaction to occur in the metallic material. The electrolyte should be composed by water (immersion or condensation), oxygen, salts, and acids or alkalis. In the track, given the difference in potential between the elements, when there is moisture on the surface an electric current will appear. In these cases, Iron will act as an anode and the rest of the elements as cathodes. Therefore, humid areas are prone to generate electrolysis problems in nearby pipelines. This is due to the generation of stray currents. Hence, it may lead to dangerous problems for metallic pipes placed close to the track.

On the other hand, humidity influences on security installations. It is especially important in tunnels. Humidity together with frosting may produce derivation in isolation materials and alteration of track circuits.

3.4. Damage on drainage system

Drained network themselves are subjected to water deteriorating effects. Most common damages are: erosion (loss of material), scouring and clogging. Therefore, it is necessary to maintain drainage systems in good conditions to optimize its management during the exploitation and maintenance phases. In addition, if climatic conditions change significantly, it will be necessary to

study the potential reduction of their capacities. An incorrect drainage performance or insufficient drainage capacity can damage the infrastructure (see Fig. 5).

3.5. Damage to a third parties

It usually refers to areas flooded upstream of the rail track due to its presence, not considering the surface that would be flooded without the presence of the rail track. Damages can be divided into catastrophic and not catastrophic. Catastrophic damages involve a serious risk of personal injury, loss of human life or affection to inhabited or industrial areas. In this case it is necessary to modify the design of the drainage and, if possible, to avoid them (it would be necessary to expropriate the buildings and lands affected).

It should be noted that risks and damages are sometimes not easily visible. For example, the phenomenon of stray currents. It is a problem when there are metal conduits nearby. These stray currents are due to current leakage from electrical circuits, when the rail is not properly insulated. In these cases, the current escapes looking for areas of lower electrical resistance. In direct current, when there is humidity in the ground and metals in the vicinity, they can generate electrolysis in their surroundings. To avoid these problems, it is necessary to isolate or to protect the rail track from current leakage. For example, performing cathodic protection (it requires that any metal pipe works as a cathode, to avoid the loss of material during the electrolysis phenomenon).

In order to avoid all previous exposed problems, it is necessary to establish measures for the conduction and evacuation of water. They will protect the infrastructure, the superstructure and the operations that are carried out in them. The solution is the properly design and construction of the different track drainage systems, which are exposed in the article.

4. Drainage systems in linear projects

4.1. Drainage in infrastructures

Track drainage is a fundamental aspect of track design as it affects track performance and track maintenance requirements. It

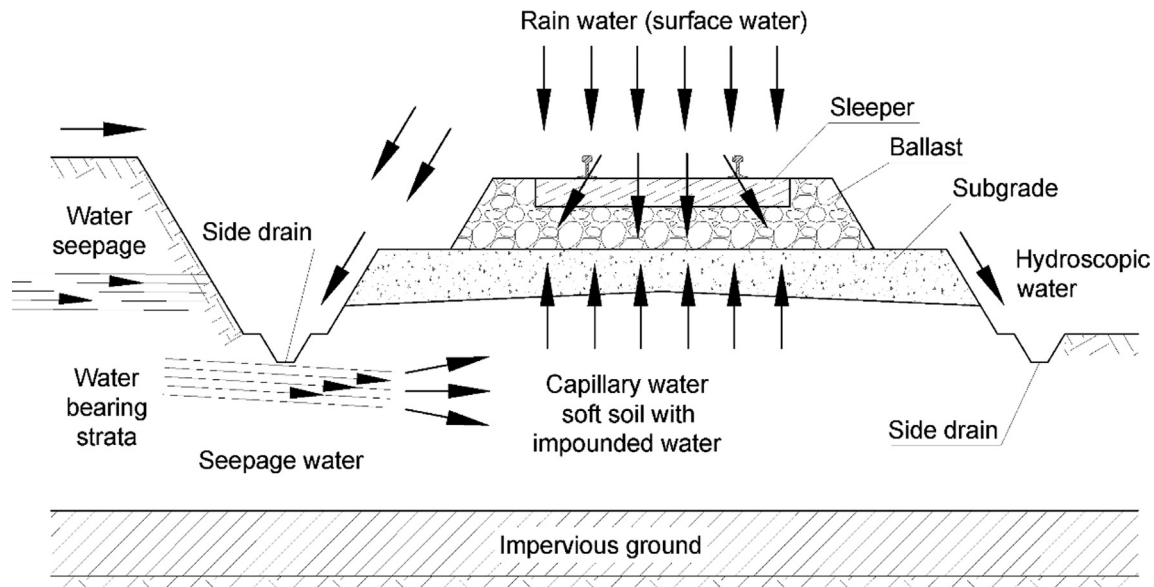


Fig. 6. Water sources in the track [1].

is a complex problem and several factors need to be considered when designing it [32]. The first thing needed to properly design the drainage system of a railway is to know how water interacts with the linear work. What is more understanding the paths followed by water and the elements that it affects. With this information, it will be possible to design an optimum drainage system for railways.

Fig. 6 shows the main sources of water in the track. They can be divided in 3 according to [1] and [33]:

- Direct water (rain, snow) it is minimized with a good internal drainage.
- Runoff water (surface water flows into the track) external drainage.
- Ground water (flow up to the track) capillarity action of water.

Hence, it is important for the drainage design to know the climatology and rainfall statistics to be able to quantify the direct water inflow. In addition, ground slope together with material type, will influence on the surface water flow reaching the railway structure as runoff water.

Capillarity head is important for railway track as precipitation leads to saturation of the track substructure from the top to the bottom. The height depends on many factors such as particle size, void ratio, density of soil particles, interconnectivity of void spaces and grain shape and roughness. Ballast capillarity raise, and head will vary from (head 6–20 cm) and (rise 5–20 cm). Those values

are the ones given for coarse and fine gravel respectively according to [34].

Water may permeate the ballast layer and flow longitudinally along the track. This flow can be: [35]: (i) Diffuse, on the flat surfaces of the infrastructure, such as the platform, the slopes, or the surrounding and. (ii) Concentrated, by the longitudinal and transversal drainage elements. e.g. ditches and channels (iii). Diffuse in porous media. Superficial drainage will be designed for the first two, and deep drainage will deal with the last one.

4.2. Classification of drainage systems in railways

Drainage systems used in railways are very similar to those used in any road project. In this case, it is more correct to talk about external drainage and internal drainage, instead of superficial and deep drainage.

There are certain general recommendations when designing drainage regarding railway track typology. Ballast track has the peculiarity of its high porosity and permeability in relation to the porosity and permeability of concrete and bituminous binders. Therefore, to carry out the water evacuation, it is necessary to slope both sides and place waterproof layers under the ballast. For concrete slab track, this inclination must be given to the concrete of the main plate, the closest to the sleepers and/or rails. In addition, to prevent infiltration from the surface to the lower layers, porous concrete on the surface (main plate) should be avoided.

Table 3
Drainage systems by railway track typology.

Railway track/drainage system	External drainage (Surface)	Internal drainage (Subsurface)	Indirect protection methods
Ballast track	Grading/ Clearing/ Embankment Lowwall, Top clearing Draining superstructure, ballast and sub-ballast	Lateral Drainage Cross Drainage Axial Drainage Drainage layers and blankets Ditches Horizontal drains Wells	Deflection barriers Protection channels Cultivated field Geogrids
Concrete slab track, tunnels, bridges	Drainage in main slab, drainage in support cups, inclination slab		

Table 3 presents a summary of the drainage elements used in each type of railway systems. What is more, a column indicating indirect protection systems has been included. These are built in the vicinity of the linear work (railway in this case), to protect it from material flows and from clogging of drainage systems itself. In addition, they act as a protection against very large avenues through mechanisms of dissipation or deflection of huge quantities of runoff water.

5. Design and calculation

In this section, the calculations used in the design of railway drainage network are presented in a simplified manner. First, it is necessary to calculate design flows, similar to the definition of characteristics loads for calculation of structures. Subsequently, geometry of the drainage elements will be designed. Finally, the solution will be materialized through its construction, which is analyzed in Section 6.

5.1. Calculation of design flow

The calculation methods to design drainage network in railways, both longitudinal and transversal depend on the country. It is the hydraulic administration who defines its own calculation criteria (e.g. Hydrographic Confederations, in Spain) when permanent channels are involved. In other cases, depending on the dimensions of the basin, simplified methods such as the Rational Method [36] or more precise hydrological methods can be employed. Both, Rational Method and the others use, as starting data, the return period, precipitation and soil characteristics. They are used to obtain the rain-flow transformation, which is the basis for sizing longitudinal and transversal drainage systems.

The Rational Method only allows the calculation of peak flows, which is useful for sizing hydraulic sections, although there is an important loss of information. The loss is more evident in the case of several hectares basins or in cases where there are permanent channels. Despite this, it is the most used and recommended method in the world [37–39].

Three approaches stand out within the more precise hydrological methods. They are: the Unit Hydrograph Method [40], the Deposit Methods and the methods of application of momentum equations (approximation of Kinematic Wave [41]).

Unit Hydrograph method estimates the drainage flows of a basin based on rainfall data whose duration and intensity do not have to be constant in space and time. However, it is based on the hypothesis that the response of the basin is invariable over time.

Design flow is expressed in terms of volume of water per time unit. It is used to design one drainage work. One key element in the estimation of the design flow is the return period, expressed in [T]-1. The return period is the probability of having one event of a certain intensity (expressed in volume of water per time unit) once every T years, in average.

Deposit models are based on the relationship between water stored in a basin, and the inflow, and outflow.

Kinematic Wave model describes the movement of water by means of the equations of continuity and conservation of momentum (Saint-Venant equations). They are a simplification of the non-permanent flow equations. This approximation considers negligible speed variations in time and space. Hence, the equation of momentum conservation is considerably simplified [41].

The above calculation methods should refer to a return period T (years). Thus, each administration establishes a value of T. It depends on several factors: i) the consequences due to the damage caused by the rains, ii) the characteristics of the channel (if there is

a defined channel) and iii) the characteristics of the drainage element.

In Spain for example, the Spanish Railways Administrator (Adif) [38] indicates that, sizing of the transversal drainage network must at least allow to drain the flow corresponding to a rainfall of T = 100 years. Some other administrations, such as the Júcar Hydrographic Confederation, asks to consider a value of T = 300 years in their calculation. This is because of regional climatic conditions. The above values are raised to T = 300 and T = 500 years, respectively, when the overflow of the transversal drainage network may reach the ballast base under the track. Adif demands calculation to be carried out with T = 500 years in the case of structures over great creeks or rivers. What is more, in these cases, simulation techniques should be employed to check the effect of the new structure upstream and downstream.

Regarding longitudinal drainage facilities, Adif requires them to be able of draining the flow corresponding to a return period of 50 years. However, it can be required to be at least 100 years on specific cases. For example, in the case of large trenches whose overflow could contaminate the ballast.

Australian Rail Track Corporation Ltd. [42], for calculation of longitudinal drainage, assigns different values of return periods according to the track category. They have divided tracks in 5 different classes. Values of required return period for each category decrease when the number of class increases. Values needed on calculation on tracks under category 1 are, T = 50 years decreasing until T = 5 years for Class 5 tracks.

High Speed Rail Authority of California [43] considers different return periods according to the type of drainage element and its arrangement with respect to the track. In addition, unlike the previous ones, it distinguishes between rural and urban surroundings. It is assumed implicitly, that greater damage will occur in urban environments. Therefore, the value of return period to be used in the design in urban environments is greater than that corresponding to a rural environment for the same drainage element. Similar to the Spanish authority, values of return period between 10 and 50 years for longitudinal drainage works and between 100 and 500 years for transversal drainage works, are suggested. Although lower values (T = 50) are allowed in rural areas.

5.2. Sizing of drainage elements in general

Once the value of the design flow has been calculated, the most common way for sizing pipes and channels with different geometries is to use Manning equation [44]. It relates flow to the slope of the pipeline, the cross section and the hydraulic radius. This is done using a coefficient that is characteristic of each material (Manning's roughness coefficient).

In the case of drains and other drainage elements consisting of granular material with high permeability (such as French drains), its drainage capacity is calculated by means of the Darcy equation [45]. This one relates the dewatered flow rate, with the permeability of the medium, the hydraulic gradient and the cross section of the duct.

In ballast tracks, physical properties of each layer (platform, sub-ballast, ballast and geotextiles or geocomposites) have a direct impact on the drainage capacity of the railway. Ghataora and Rush-ton [46] propose the following differential equation to describe the flow of water over ballast and sand. Where K_b and K_s are the permeability of ballast and sub-ballast, respectively; h is the total saturated height; S_y is the porosity (specific yield), q is the intensity of rainfall, m_s is the thickness of the saturated sub-ballast layer and z_b is the height of the impermeable layer (see Fig. 7).

$$\frac{\partial}{\partial x} [K_s m_s + K_b (h - z_b - m_s)] \frac{\partial h}{\partial x} = S_y \frac{\partial h}{\partial t} - q$$

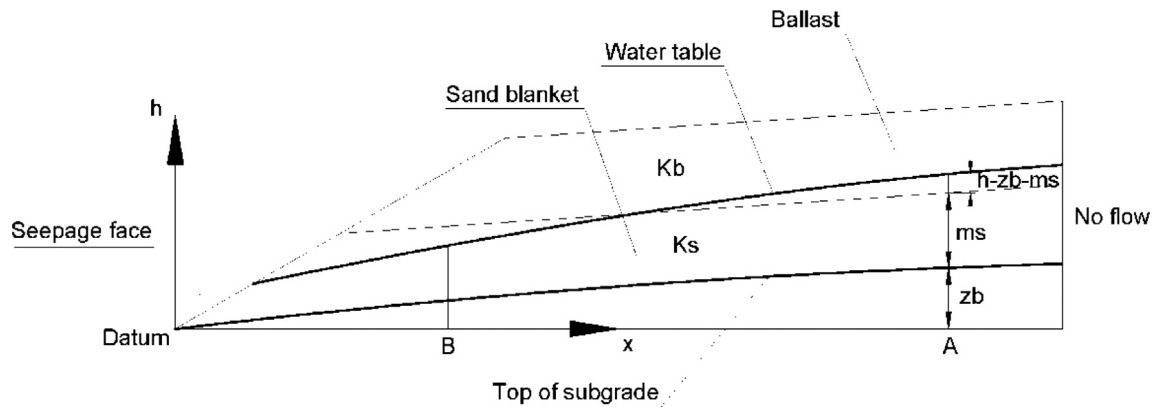


Fig. 7. Scheme of drainage calculation.

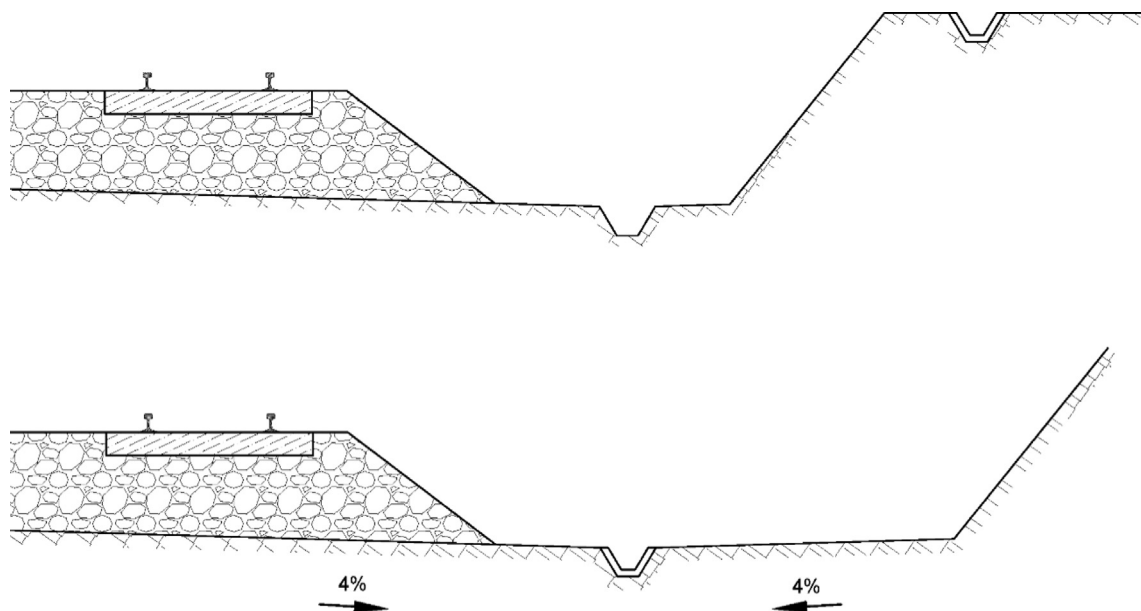


Fig. 8. Typology of the basic ditches close to the railroad example taken from [44].

This equation is composed by three terms. The first one represents the flow through the sand blanket and ballast. The second one is about the water taken or released because water table rises or comes down. Finally, the third one deals with the recharge entering the system.

In the case that conduits are crossing drainage pipes, (straight pipes with the same section at the entrance and the exit) a characteristic curve can be defined to consider its influence. These curves relate the flow rate with the height of the water sheet immediately upstream of the entrance section of the conduit. These curves are experimentally deduced, and they depend on the geometry and type of canal embouchure. In general, hydraulic design requires all transverse drainage elements to work with input control [38,47].

Flow nets can be useful to design internal drainage. The internal drainage design approach proposed by [33] is based on limiting the saturation of the subballast layer to prevent excessive deformations after cyclic loading under saturated conditions. This procedure assumes that the subgrade is impervious (this is on the conservative side when the subgrade is permeable). The limitation of maximum saturation is given by the maximum height of saturation $H_{\max}$ of the subballast layer. Values of between half and one fifth of the ballast layer height are considered reasonable. Once

the value of $H_{\max}$ has been obtained, the maximum length of the flowpath, L_{flow} , is obtained based on the subballast hydraulic conductivity (k), the rainfall intensity (q_i), and the slope of the drainage layer (S_{dl}). Results can be presented in terms of design charts.

6. Construction

Construction of drainage elements must be considered during all the construction phases in railways. Initially during the execution of infrastructure elements and then during the execution of the elements of the superstructure. Elements of the drainage system of railways are presented below. These elements are divided into two groups according to their location and their objectives: external drainage (out of the track) and internal drainage.

6.1. Examples of drainage works in railways

External drainage tries to: (i) Collect and evacuate the runoff water on the cut slopes, (ii) Collect and evacuate the water of the platform itself and (iii) Control the phreatic surface if it is close to the platform. Therefore, the surrounding soil profile must be perfectly known. Elevation of the track and the topography of the area should be as well understood.

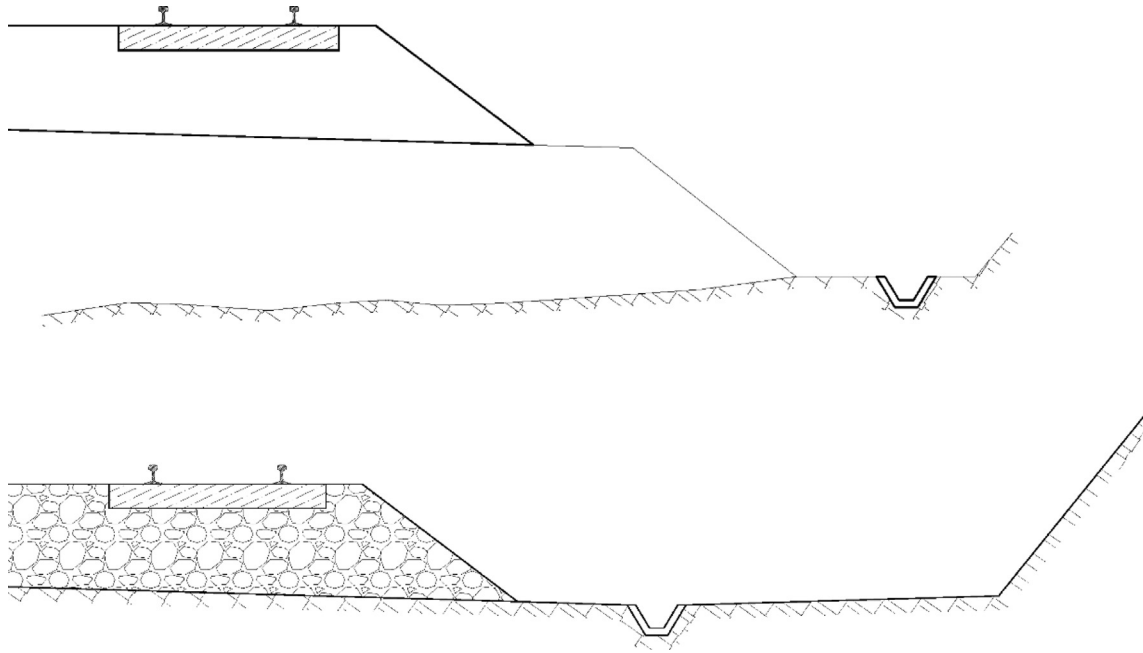


Fig. 9. Typology of the ditches taken from [44].

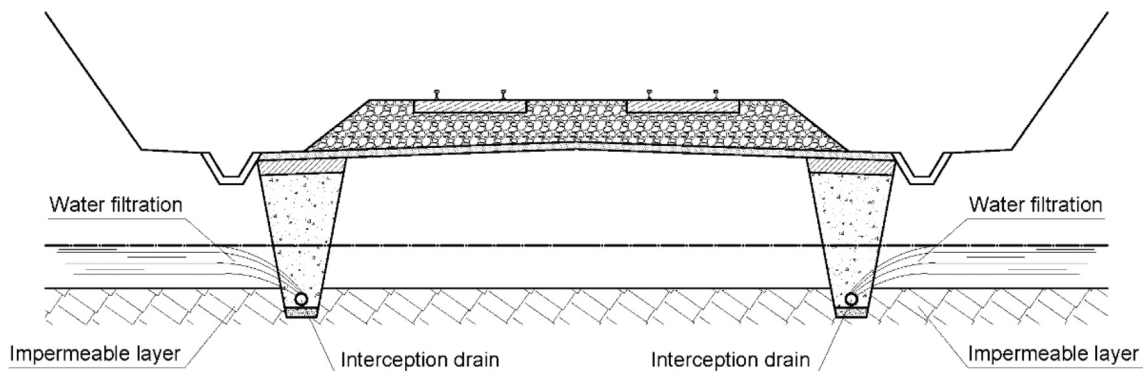


Fig. 10. Longitudinal basic deep drainage. General cross section detail.

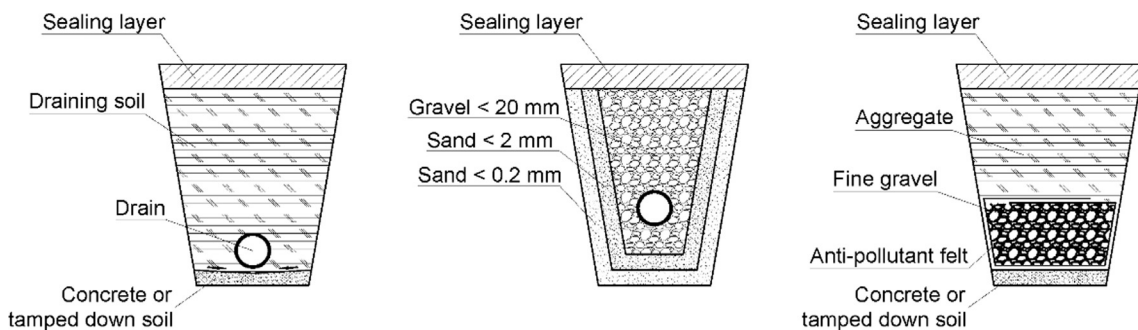


Fig. 11. Usual typologies of drainage ditches.

External drainage is also known as interception drainage, since it must intercept and divert all water from underground sources and channels (see Fig. 8). The most used elements to accomplish efficient external drainage, are ditches or trenches. This is generally the case in any linear work. The simplest form to classify ditches is based on its location in the linear work: (1) grading (clearing), (2) guard (clearing crown), (3) tunnel, and embankment foot, depending on its position (see Fig. 9).

On the other hand, deep drainage has several missions: (i) to intercept diversion of underground currents, (ii) to prevent groundwater from reaching the track platform, (iii) to intercept and lower the water table. Deep drainage is also known as internal drainage (see Fig. 10). It is divided into longitudinal or transversal drainage network, depending on its relative position to the track. Whether it is placed parallel or perpendicular to the axis of the track respectively.

When surface drainage systems do not evacuate all the water that reaches the structure, it can reach the platform. Hence, it is necessary to provide systems that evacuate water from this element of the railroad structure. In order to do this, drainage ditches are arranged in the platform. Fig. 11 shows examples of drainage ditches used in Spain. Basically, they consist of a ditch topped by a sealing layer where filter materials such as gravel is poured. Generally, a drain is placed on the bottom, depending on the permeability of the platform. These pipes need to be suitable for the water flow and strong enough not to suffer large deformations. They should be installed on slopes of at least 1% or 2% for smooth and corrugated pipes respectively. When the ditch is waterproof, the screed can be concreted, or the soil can be compacted. If there are several filling materials, it is advisable to use a filter material such as geotextiles to separate them.

Drains are divided into three types: (i) lateral, (ii) transverse and (iii) axial. This classification is made according to the direction of the drain axis. If it is parallel to the railroad axis, (lateral) per-

pendicular (transverse), or coincides in plan with the axis of the tracing (axial). These drainage elements are difficult to repair because they are located in the platform, under the track. Therefore, their correct execution is essential to avoid subsequent corrective measures.

In the case of a ballast track, drainage construction starts at the same time as compaction and profiling of the layers under the subballast takes place. Railway drainage guidelines recommend the groundwater level to be between 0.8 and 2.5 m below the rail head, depending on local conditions. The lower limit value is only allowed if the subbase under the ballast is good (Platform P3, Classification according to UIC), the frost does not penetrate, and the groundwater flow is low. This recommendation is provided in [48].

Not only a good compaction, isolation and waterproofing of these layers is necessary, but also a certain inclination is needed. The slope varies depending on the type and characteristics of the railroad but it is normally between 3 and 5% (see Figs. 12 and 13). Rushton and Ghataora [49] Proposes a slope of 5% on the sub-

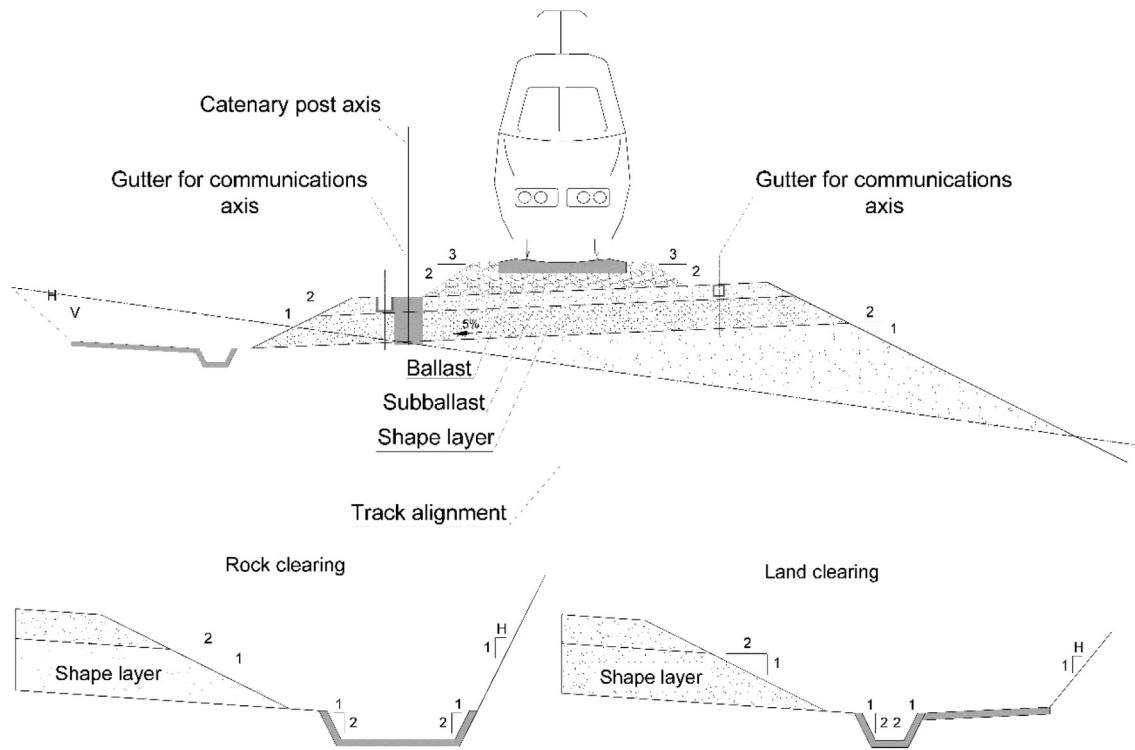


Fig. 12. Ballast track scheme, Simple track.

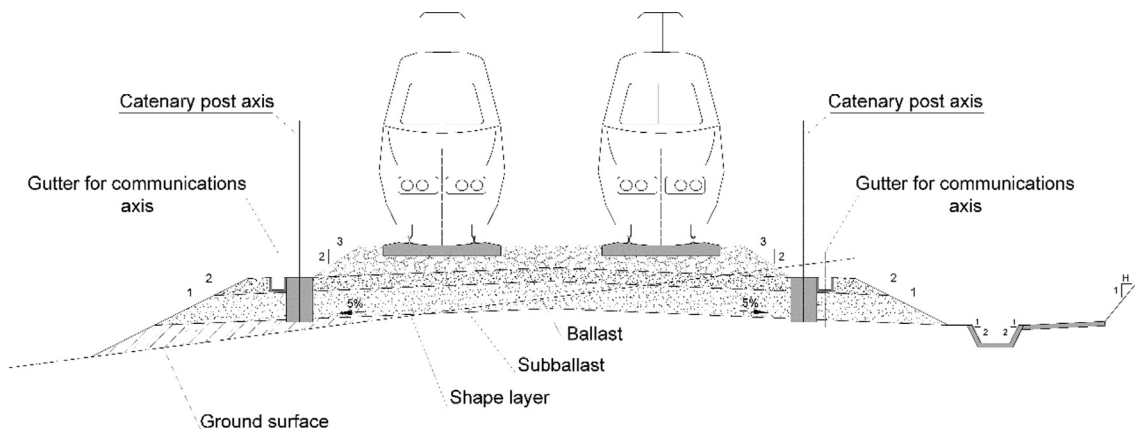


Fig. 13. Example of external and internal drainage in double track.

grade whenever possible to accelerate the drainage time. This slope can be reduced when the track is on embankments treated with cement.

It is necessary to differentiate between straight and curve sections. If the section is straight, it is necessary to give slope to both sides of the platform. However, when it is in curve, the super elevation of the curve could be enough. It is also different for single and double track cases. In cases of single-track providing both sides with a slope between 3 and 5% is enough. When dealing with double-track sections or two platforms close together, a drain on the central axis between both tracks may be needed.

In tunnel sections, it is necessary to have a drainage element; this can be lateral (if it is single track) or central if it is double track. The slope towards the drain should be 2%. Independently of its sections (vault or in a screed) Fig. 16.

Central drains are used, where there are more than one pair of tracks. Drains are similar to side drains with similar catch pits (see Figs. 13 and 14).

In the case of slab track systems, if the platform quality is poor, it is generally necessary to improve its drainage using deep drainage elements. Normally the evacuation of the water is superficial. It is usually evacuated by the transverse slope or the cant of the filling concrete. A longitudinal central drainage element placed between both tracks can be used, so that approximately half of the surface water of both tracks flows inwards. When there is ballast over the structure (see Fig. 15) it is recommendable to give it some inclination to let water flows out of the structure.

In cases of double tracks, an impermeable drainage channel (concrete or asphalt) can be built between both tracks, allowing surface water to flow until the extraction tubes. In case of no central drain (straight section), the concrete slab will be built with a slope profile towards the outside.

Before concreting the screed, longitudinal and transversal drainage network must be made. In the case of a double track, internal drainage can be designed in several ways and it can be composed of:

Drain pipes in the axis of the intersection and two superficial grooves on the outside of both tracks. This outline is usual in stations.

Drain pipes on the outside of both tracks and superficial groove on the track axis. This layout is shown in Fig. 17 and it is commonly used in tunnels.

Drain pipes on the axis of the intersection and gutters on the outside of both tracks. Sumps for the evacuation of superficial grooves water should exit. Tubes or pipes placed transversal to the track oriented towards the deep drainage network or to the ditches are the most common solution employed. The sumps and the outlets must be protected against blockages and entrances of small animals. This can be done by placing grids.

Generally, through the lateral slope, water can easily be evacuated from the platform, both in the viaduct section and in the tunnel (see Figs. 16 and 18).

In the slab track, the biggest problems are found in the joints and contacts between elements. As an example, in the Stedef system, the most common problems are due to the lack of sealing between the base of the sleepers and the main slab. One common solution is to introduce a fill pad to prevent water from eroding that area. An example is shown in Fig. 19. In addition, soles or watertight elastic elements, are also employed to avoid direct contact between sleeper and concrete. They avoid contact between concrete-concrete and prevent water from entering within these gaps.

External drainage systems on the rail track and on the slope (cut or embankment) are executed in a similar way than those presented previously for ballast track (ballast track or slab track). It is important to stand out that it is necessary to give a certain slope to evacuate the water from the platform as soon as possible.

After construction and during operating conditions, all drainage elements must be regularly inspected and rodded, especially after heavy rain or even if it possible during a heavy downpour when any problems are best observed. It is recommendable to check all the elements of the drainage system periodically and specially during and after storms or flood conditions if possible [15].

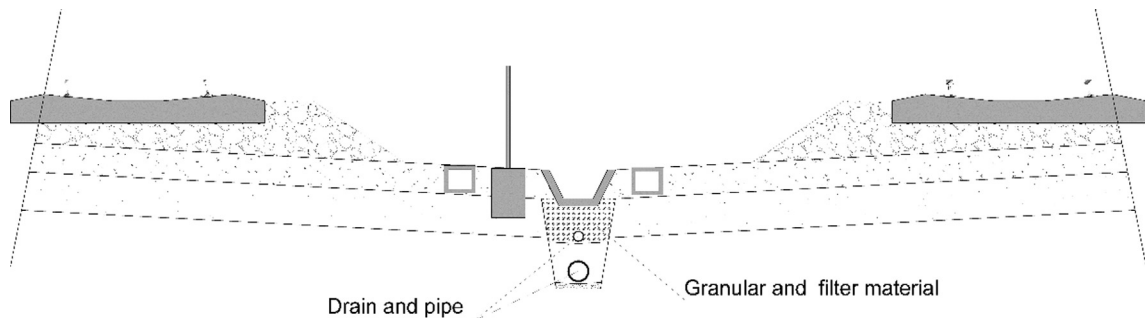


Fig. 14. General cross section in ballast track, two platforms. Central drain is necessary.

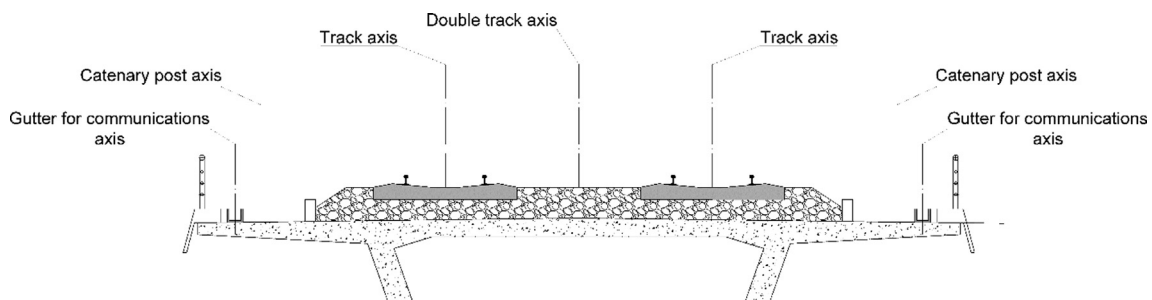


Fig. 15. Double ballasted track. Viaduct cross section structure.

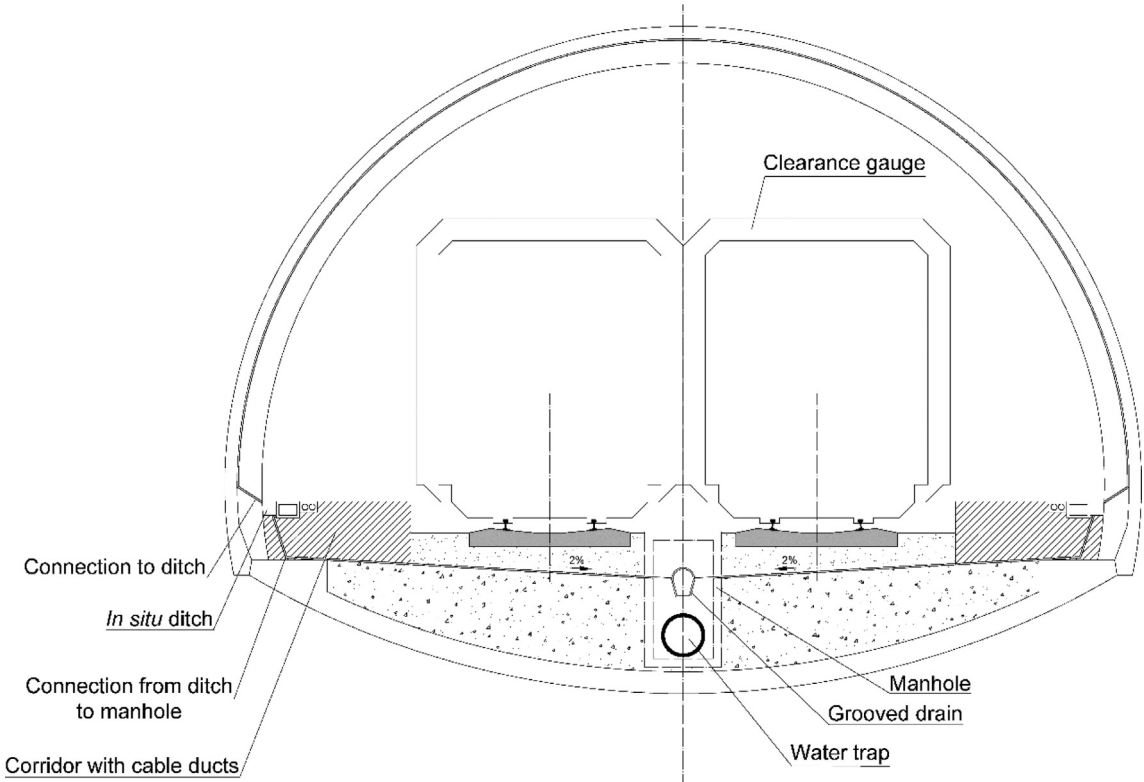


Fig. 16. Double track. Tunnel cross section.

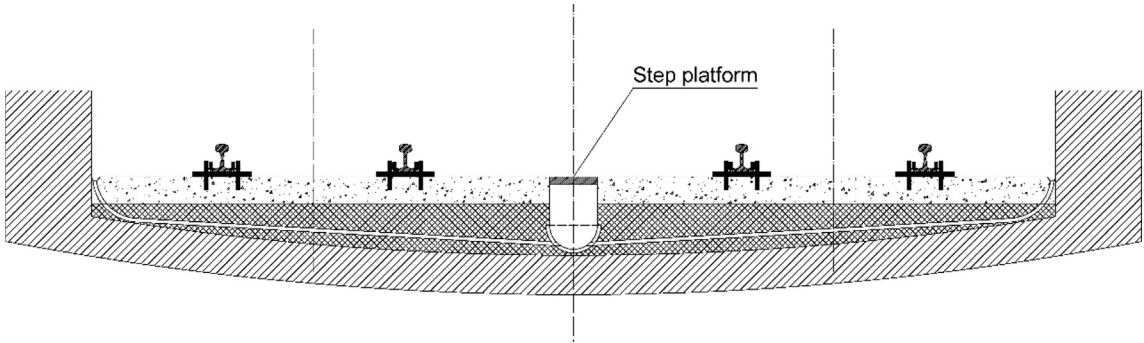


Fig. 17. Slab track direct fixation system. Drainage detail. Tunnel cross section.

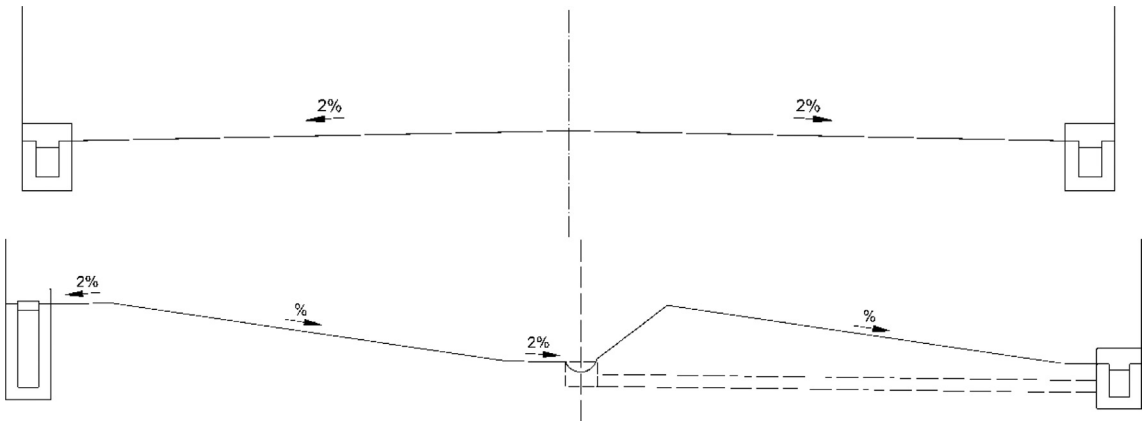


Fig. 18. Recommended inclination for slab track in tunnels scheme (straight-curve).

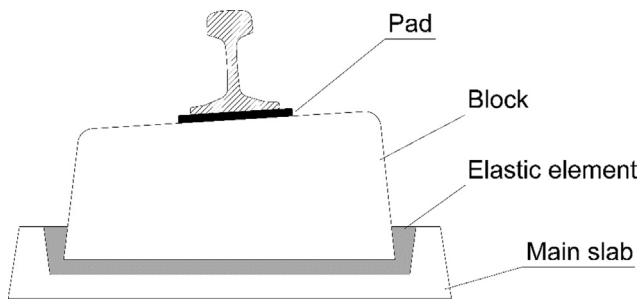


Fig. 19. Impermeable system under blocks.

6.2. The use of drainage materials

Several materials can be employed to provide track drainage going from simple materials such as stone aggregate, to more advanced ones such as geosynthetics. Besides, pipes and hot mix asphalt can also be used as drainage materials.

Pipes are used to transport water longitudinally and laterally under the track. They can be made of different materials: steel, iron, concrete, plastic, etc. They need to be suitable for water and strong enough not to suffer huge deformations. They should be installed on slopes of at least 1% or 2% for smooth and corrugated pipes respectively.

Graded Aggregate, high permeability coarse aggregate is usually the most cost-effective solution. To avoid clogging with time and ensure its long-term performance size related filter criterion should be followed [18,50–52].

Geosynthetics includes a wide variety of products such as: geotextiles, geocells and geogrid. Besides helping with drainage, they have been proved to reduce track deformation and degradation [8,49,53–58]. The use of geosynthetics under the ballast layer as a filter blanket has been considered for more than 35 years [59].

Geotextiles can be woven or non-woven and their main use is to separate materials, as filters. Their equivalent open size should be adequate. To provide separation their open size should be lower than the D85 particle size of the fine-grained soil [18]. Geotextiles have the capability of providing drainage in the plane of the geotextile; however, the amount of drainage in the planar direction is typically very small. Koerner (1990), notes that, aside from geocomposites, nonwoven geotextiles have the highest in-place permeability [60]. Fatahi et al. 2011 [59], showed that non-woven geotextile layer introduced as a filter material reduce the maintenance cost of the railway structure and the thickness of the subballast layer [59].

Geomembranes are commonly impermeable, flexible geosynthetic sheets. Their main function in track substructure application is to prevent water infiltration and avoid detrimental water effects on the subgrade such as softening or shrink and swell volume changes [1]. They can also be used to raise drainage surface in the track substructure and then provide effective gravity drainage. A potential problem with the use of a geomembrane is the possibility of trapping excess water beneath the membrane. Resistance to lateral sliding must also be considered for each specific application where a geomembrane is used. The membrane may have a relatively low friction between it and the ballast placed above it, and so the possibility of lateral ballast movement on the membrane should be considered.

Hot mix asphalt is impermeable therefore, it reduces the access of water to subgrade. Its application is similar to a geomembrane used to raise drainage surface. A potential problem with the use of HMA underlayment is the possibility of trapping excess water beneath the HMA [1].

6.3. Recommendations and guidelines about railways drainage

In general, it is common to find guides and standards all around the world on drainage. However, it is less usual to find ones dealing with drainage in railways in particular. This section shows that these standards and practical guidelines are used today in the design and calculation of railway drainage systems.

In Spain, ADIF regulations [38,61] gives some recommendations on how to construct ballast track drainage, single track and double track for Iberian (Spanish) gauge and for standard gauge. The old designs followed the NRV regulations [47]. Nowadays, the new designs are included within the UIC European recommendations [48] and in the current Adif regulations [38,61]. Recommendations are given on how to calculate drainage systems in the platform and the dimensioning of the drainage elements [47,62]. Subsequently, the state dictates new recommendations regarding drainage systems on the rail track.

The current Spanish infrastructure administrator has several regulations dealing with calculation of drainage elements [38] and [61] they include the definition of track sections with their corresponding construction details where drainage systems stand out (new guidelines from June 2008).

The UIC regulations, deals with drainage of the subgrade in section 2.8 from the standard [48]. It establishes the difference between, ground water (at a distance of at least 0.8 m under the head of the lane) and surface water, especially rainwater and runoff. These guidelines gives indications of the layers inclination depending on the materials and the compaction. It specifies the calculation of the runoff coefficient and provides indications to calculate the filtering materials (or filter materials).

Open and specific regulations and guidelines related to drainage in railways from the United Kingdom [63], India [64], Australia [42], Israel [65], Southeast Asia (Hong Kong [66], Japan [67]), and the USA [43,68,69] have been analysed. In relation with United States regulations, one of the most complete in terms of drainage in railways is the one related to high-speed California [43]. Section 8 of this regulation is dedicated exclusively to drainage. It presents the main policies, recommendations and guidelines in relation to country regulations. It takes into account the design of surface and underground drainage, drainage in structures such as viaducts and tunnels and ways to fight against superficial erosion. In addition, in the geotechnical section it talks about superficial and deep drainage: in walls (backfill), in the surroundings of the slopes (slopes), under embankments, in flood plains, in saturated zones (wet conditions), among others. Drainage is also considered in their other states rail regulations (e.g., Kansas [68], Florida [69]) in some cases public and private guidelines are considered.

United Kingdom railways policy also contains in [63], a section dedicated to drainage. It describes the mission of the layer formation (subgrade) and it talks about improved drainage. It provides as well recommendations about gradients in tunnels. Annex B give some recommendations to solve typical problems of drainage as well as advice about maintenance of the drainage network. At the end, drainage construction schemes are provided through the cross sections of the track.

The regulations of Hong Kong in [66] are based on Eurocodes and English regulations and standards. They are locally adapted to the requirements of the Hong Kong region. The guide establishes overall design criteria for structures on roads (highways), undergrounds and railways around the country.

The Israelis Railways design guidelines used for speeds up to 250 km/h [65] talks about drainage systems in its first part. They provide detailed annexes with diagrams of drainage sections and drainage ditches. Refer to the ISR Planning Branch [65] for more detail of the designs.

India in its guidelines on erosion control and drainage of railway formation [64] gives specific recommendations to control erosion (part A) and drainage in its railways (part B). In part A, they deal with erosion in a complete way, from the main existing mechanisms of erosion (natural and artificial) to the different types of solutions to solve them and their limitations. In the same way, they offer some recommendations to select the most suitable system of erosion control depending on: the speed of water fall, the situation of the system and the height of bank/cutting (the height of the cut, type of soil). In part B, it describes the mechanisms of water entry to the railway substructure. It outlines the conventional drainage systems, how to calculate and design them and how to build them. It gives recommendations on the use of geotextiles in drainage. Indian guidelines are a complete manual of surface erosion and drainage treatment, as they describe the main problems associated with erosion and drainage and how to overcome them.

Australia in their Engineering practice civil manual of track drainage design [42]. They are guidelines designed to perform a preliminary calculation and dimensioning of the drainage elements. In addition, some guides for their subsequent construction are also given. The document presents examples of calculation and dimensioning of the elements. They suggest the use of the rational method as a basic method of calculation. In Section 4 they deal with the construction of the drainage system. They clearly describe the process, from the measurements of the situation of the elements to the necessary requirements and steps needed to build the different drainage elements (surface drains, deep drains, drainage ditches, vertical drainages, horizontal drains, isolated drainage pipes, drains, other types of drain to be used). In the appendices, steps to help in the calculation phases and design of the drains are also presented. It is a very technical guide, based exclusively on railroad drainage.

7. Adaptation and resilience in railway drainage

Currently there is evidence of global climate change. Although it is very difficult to discern exactly what part of this modification has anthropogenic causes, (such as the emission of greenhouse

gases) and what part is due to the climatic modifications that have existed throughout the history of the planet (through periods of heating and cooling or glaciations), it is evident that the current trend to warming is aggravated by human activity [70].

In the coming years, changes in temperature and rainfall are expected as part of this climate change. Variations in annual or seasonal average values, and in extreme events are as well awaited (see Figs. 20–24). Greater severity and frequency of rainfall and drought extreme events are expected. This will impose new requirements in the transport systems sector so that, they can maintain their functionality and service to society.

Transport infrastructures, and especially the railway lines, will be one of the affected sectors. The adaptation or the increase of resilience of these infrastructures to climate change is a major challenge. The process will always include a degree of uncertainty based partly on considerations of the expected climate. This uncertainty will be reduced with the advance of science in this field.

As presented before, drainage system is a key factor in railway performance, therefore, it is necessary to design it properly according to the new climate conditions and to provide protection to the different drainage elements. This protection can be indirect through measures that reduce the flow of runoff and thus reduce the effect of erosion of materials, (such as plantations on slopes and clearings close to the structure), or more direct such as the installation of flow deflection barriers or anti-clogging mechanisms in the drains or in the vicinity to avoid the destruction or malfunction of existing mechanisms (Table 4).

Many countries have already adopted policies or measures to mitigate climate change. Nevertheless, the adaptation of their transport systems to the inevitable effects of this change is still at a much more initial stage. Even the infrastructures that are being built today, (whose lifespan is expected to exceed 100 years in many cases) continue to be designed based on historical climate records, which are no longer a reliable source for predicting future situations. The application of this type of design strategies will lead to a considerable increase in its maintenance costs, and an increase in service interruptions. In the worst case, they can lead to the collapse or failure of any of its components that can end in catastrophic situations.



Fig. 20. Permanent way destruction due to flood occurred in Seville, Spain.



Fig. 21. Totally flooded rail tracks (Massachusetts 2018).



Fig. 22. Totally flooded rail tracks (Massachusetts 2018).

Before proposing specific measures of action on existing infrastructures, it is important to assess the possible scales and approaches for action. Two scales of action are basically considered: The element scale and the network scale. The first one aims to increase the resistance of the critical components individually. The network scale is more focus on increasing the redundancy of the system in critical areas, duplicating routes or systems. Regarding the action typologies, they can be divided into non-structural and structural ones. Non-structural measures are related with land use planning in the area. However, structural measures include the execution of works that modify the infrastructure.

On the other hand, the activities aimed at adapting, or improving the response of the railway system to climatic events, are not limited to already in-service infrastructures. In cases of new structures, they should be considered in all phases of their life cycle. i.e. In the research phase considering advances in climate modeling. In the generation/revision of regulations phase by updating the regulation of their drainage systems. In the planning and design phase by improving the integration of the infrastructure layout, the management of land use, and the risk maps such as floodplain. In the project or construction phase by building barriers to contain floods. In the exploitation phase by means of personnel training, taking specific measures for traffic and circulation and monitoring or



Fig. 23. Drainage problems in track structures in north Spain (2019). Station flooded.



Fig. 24. Track failure due to hard rains. South Spain (2018).

improving traffic management. Finally, during the maintenance phase of the railway infrastructure.

Currently several activities are key to progress in this line within the rail sector. They can be divided into two groups: the

ones related to knowledge and control of the situation, and the actions related to possible improvement actions. The first group will include the analysis of the vulnerability of railway networks from their planning phase to their service, to be able to detect

Table 4

Acting modes and description of proposed measures.

Type of actuations	Type of drainage	Recommended measures
External protection	External drainage	Increase in design flow
Internal protection	Internal drainage	Increase of slopes in lower layers
Surroundings protection	Drainage in the vicinity of the infrastructure	Increase return periods Increase the dimensions of the drains Gradual and progressive increase in grain size in used filters
Erosion and clogging protection	Auxiliary drainage structures	Slope plantation

the sections or elements that represent critical points in front of a specific climatic event. In addition, real-time monitoring in vulnerable sections, including control of the state of the rail track and its hydro-meteorological conditions are also part of the first group activities. The second group takes care of the optimization of the maintenance network works, which in many cases can solve the situation. The optimization of emergency response actions when it is assumed that these situations will be reached. What is more they will deal with the proposal of adaptation or re-design measures, in necessary cases.

Nowadays, there are initiatives in different countries that have been more focused on the diagnosis of the situation than on the implementation of measures and the analysis of their results. These are based on the creation of risk and climatic threats management systems on railway infrastructures. Table 5 shows a compendium of the most significant ones. Management and planning of railway infrastructures entities must invest resources to imple-

Table 5

Description of significant measures taken to counteract climate change.

Country	Intervention/mitigation action	Description
EUROPE	“Adaptation of transport to climate change in Europe. Challenges and options across transport modes and stakeholders” [71]	European Standards
AUSTRIA	KLIWA Project (Adaptation of ÖBB to climate change) Austrian Federal Railways (ÖBB) faces risks related to natural disasters and has implemented a system for managing them since 2008, focusing on prevention rather than immediate response.	It analyzes the existing information of traffic interruption events since 1990. Information was not collected automatically, but it was structured as part of the project. In the project, event information was analyzed and documented, and the damage database of ÖBB was expanded. The previously developed natural risk maps were expanded and/or linked to climate projections [72,73]. This work follows the classic cycle of risk analysis. Prevention actions include risk mapping, forest protection management systems, a meteorological information system (infra web portal: wetter), warning systems for events such as avalanches or floods and in-situ emergency training. Natural hazard maps have been created covering the 5700 km of rail network to analyze/assign potential risks, establish priorities and use the information in long-term planning considering climate change. A specific team specialized in natural risks is responsible for the maintenance of 165 km with risk of landslides and avalanches.
SPAIN	Adaptation of railway operations (RENFE)	The Spanish railway services operator has included a tool for the prediction of adverse weather events specifically adapted to the railway system. This was done to facilitate the development of management strategies for pre- and post-crisis situations in real time.
UK	Review and application of UK drainage Standards and recommendations. NetWork Rail [74] Rebuilding the Dawlish railway line Track Water- Project [4]	Network Rail, the operator of railway infrastructure in Great Britain, published in 2010 its first Manual of Railway Drainage Systems. It includes impacts of climate change on the regulation of railway drainage design, for the first time in the United Kingdom. It has been applied in: • The new Borders railway connection (Borders Railway, 2014) in Scotland, which connects Edinburgh with Borders and Midlothian. • The main floodplains of the Scottish railway lines have recently undergone a Flood Hazard Analysis. As a result, flood ponds have been built in Drem and Dalmarnock. The capacity of the siphon chamber has been increased and a flood basin has been designed for Penmanshiel. After a storm in February 2014, the coastal railway line in Dawlish (United Kingdom) was seriously damaged. A section of a dike and the foundation under the track were destroyed by the effect of the large waves during the storm, leaving the track without support. The Dawlish station was also affected. The initially damaged section was 80 m long and reached 100 m after a second storm. Measures were taken in the short and long term. The project Track Water address four challenges: ‘understanding drainage system capability’, ‘safe and efficient drainage inspections and monitoring’, ‘improving drainage system performance’ and ‘improving drainage asset management decision-making’. The project includes a novel Internet-of-Things (IoT) sensor network to capture the real-time conditions of drainage assets, real-time data models to predict flood risk, and end-user decision-support visualization tools to support intelligent rail surface-water management. The main advantages of the project: (i) Support for both manual and automatic (IoT sensor-driven) inspections of rail drainage assets, (ii) A Real time overview of the state of the drainage network, and, (iii) A trusted decision-support system that enables operatives to conduct predictive maintenance.

(continued on next page)

Table 5 (continued)

Country	Intervention/mitigation action	Description
	TRaCCA — Cooperation between Network Rail and the Office of Meteorology on issues of climate change impact, Great Britain Between 2010 and 2011, Network Rail and RSSB commissioned the Met Office to analyze the possible impacts of climate change on the rail network. Great Britain, as part of the project 'Tomorrow's Railway and Climate Change Adaptation' (TRaCCA) [75].	The Bureau of Meteorology worked with experts from the rail industry to define a list of aspects related to climate change that were potential areas of interest for the stakeholders. Later on, a more in-depth study was performed in a selection of priority areas. This included issues such as the buckling of railroads or the flooding of facilities. During the work, the Bureau of Meteorology supported Network Rail in the preparation of its response to Adaptation Reporting Power. This process started with the Climate Change Act 2008 and many infrastructure operators were asked to report -their progress in the field of adaptation to climate change.
NORWAY	Cooperation between transport entities and experts in meteorology and hydrology. Climate and Transport Project (2007–2010)	The Public Roads Administration and the Directorate of Energy and Water Resources of Norway, in collaboration with the National Railway Administration and Meteorological Services, have developed the xGeo tool, an online tool for risk assessment and for flood monitoring and forecasting, landslides and avalanches. The idea of combining information from different sources such as hydro-meteorological information and maps of the railroad network in a single tool came up after a major storm near the city of Trondheim in 2006, which caused major interruptions in transportation around the area.
GERMANY	Adjustment priorities of Deutsche Bahn (DB)	The Deutsche Bahn acts fundamentally in these 4 areas: 1. Participation in a working group for the revision of the regulations, with the German Standardization Institute (DIN). The objective of this group is to define the regulations required to adapt to climate change. 2. Review of protocols and operation plans before extreme events, by DB-Netz (responsible for the railway infrastructure). 3. Research on adaptation strategies to climate change. DB is working together with the German Federal Railway Authority to open new research projects in climate change adaptation strategies. The first projects were launched in 2014. 4. DB has participated in a process led by the Federal Environment Agency for the development of the second Adaptation Action Plan of the German Strategy for Adaptation to Climate Change (APA2).

ment adaptive measures to climate events (such as the expectation of extreme rainfall to increase their intensity and frequency in the next years). It requires the generation of tools to evaluate and compare alternatives including the cost of not acting. These tools should at least include economic criteria. However, they can be more refined and consider more global consequences and monetize other type of costs. In view of the upcoming predictions due to climate change, and based on the analyzed regulations and the proposals that are already underway, it is necessary to provide auxiliary mechanisms. These mechanisms should allow a safe and efficient drainage of the infrastructures in general and on the railways in particular. Several solutions can be proposed depending on whether it is a new design element or a modification of an existing one. Thus, several types of action can be considered. For new construction elements, it is recommended to oversize them, increasing the return periods and increasing considerably design flow rates. Besides, drainage slopes and drainage capacity should be increased. They should be at least twice the current ones. In structures such as viaducts or bridges the slope of the platform can be increased. In tunnels it will be necessary to provide greater dimensions drains than the current ones. In addition, special emphasis should be placed on their entrance and exit slopes. For existing elements, two types of action are proposed: (i) modifying existing elements, based on new calculations. This may involve demolishing old drainage systems and building entirely new ones, or (ii) supplementing the existing elements with additional ones without modifying them. All this needs to consider the budget for each case.

Due to climate change and global warming environmental scenarios are going to change differently as infrastructure managers though. Therefore, is necessary to go further the current systems. The existing structures in general and railways structures in particular have to be ready to these new changes.

7.1. Drainage design flowchart

As presented before drainage system design and maintenance has not always taken the deserved attention even if it is a key factor on railway performance. Currently, there is no a standardize protocol or procedure to solve drainage problems and to increase railway infrastructure resilience. It is still a problem with solutions in development. Thus, the authors want to provide a standardized design tool to improve the design of new drainage systems and remediation works on existing structures and elements. This design tool is presented in Fig. 25 in form of a flow chart. It summarizes the most important aspects of the design procedure and the potential options with the aim of increase the resilience of the railways infrastructures. It presents the different steps and aspects that should be followed to develop and design effective drainage elements and systems, adapted to new climate conditions and therefore increase the infrastructure resilience. Two of the new aspects presented in this new design tool are: the resilience Key Performance Indicators (KPI) and the feedback from the continuous analysis. The main Key Performance Indicators (KPI) related with resilience that administrations should considered are the following five:

- Assets failure proe million train-km
- Disruption
- Efficiency of use of the network
- Tracks with permanent speed restrictions
- Tracks with temporary speeds restrictions

The feedback from the continuous analysis of the railway networks, to the design process is represented by the boxes in blue in Fig. 25. This analysis goes form their planning phase to when the infrastructure is in service.

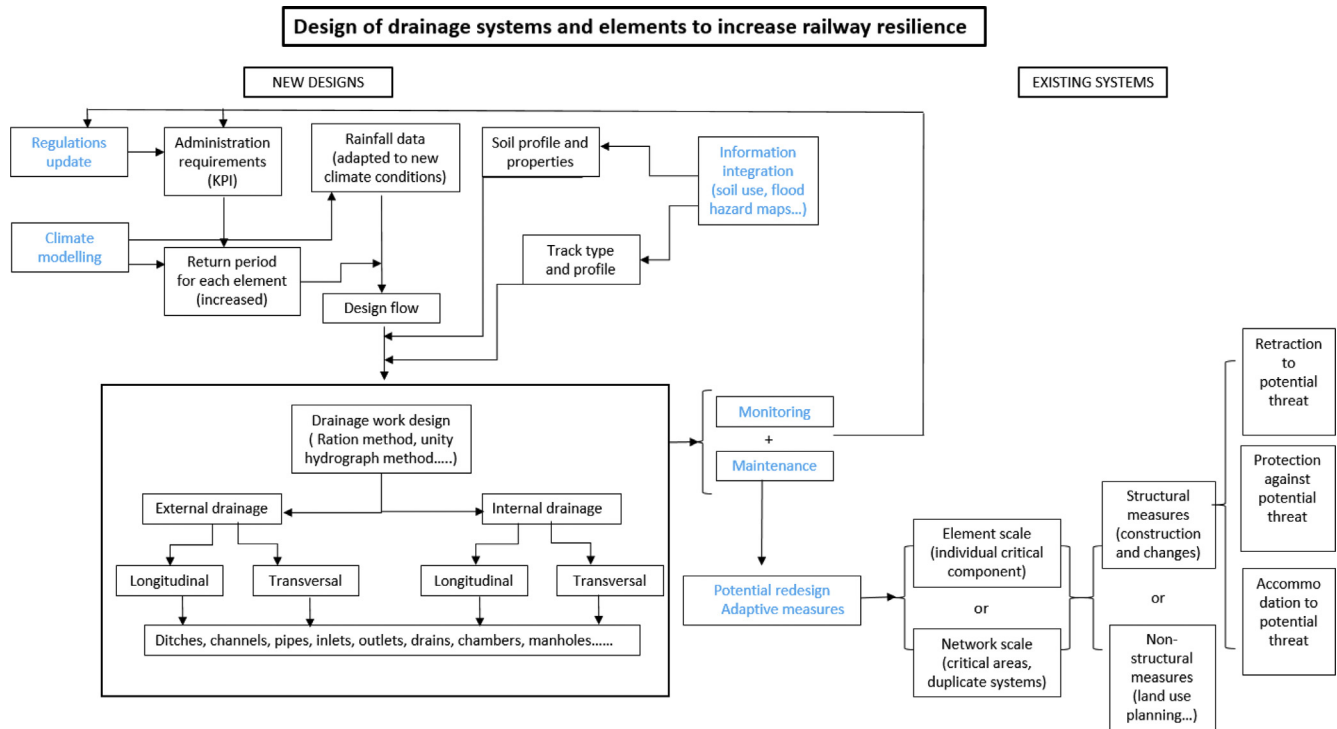


Fig. 25. Flow chart of the drainage design process. External data sources and models are in blue for highlighting new resilience multipurpose approach.

It is worth nothing that the design tool should be specific for each site as the soil properties, rainfall data and administrations requirements are site-specific so there is a limitation on implementing successful solutions to different areas without the required analysis.

8. Conclusions

Thanks to this work, the authors intend to give an overview of the drainage systems used currently in the railway infrastructures. Therefore, a review of the state of the art has been made. What is more, an analysis of most important problems occurring in the railway structure and ways to solve them has been performed. In addition, an overview between ballast track systems and slab track systems, providing infrastructure, materials and operations has been also provided.

It has become evident that drainage system in civil engineering infrastructures is very important. Most common systems and regulations in relation to the subject of drainage in rail infrastructure have been discussed, as well as, some initiative to develop solutions to it. It has been shown that there is a lot of experience at the international level. However, current measures do not contemplate significant climate changes in the short term. After reviewing current designing methods, it has been seen that return periods are sometimes not conservative enough. Therefore, the considered design flows are too small. Higher time periods T and higher flow rates are needed in new calculations.

Due to climate change, problems caused by water in this type of structure are increasing. Therefore, it has been proven that drainage system design and dimensioning is becoming obsolete and are not resilient enough. In this sense, this study presents itself as starting point to propose initial solutions to combat this obsolescence by adapting current systems for these near-future changes and increase its resilience.

There are a lot of examples around the world where inspection, maintenance and repair of all parts of the drainage system have been neglected over decades. In other cases, drain maintenance has low priority in the overall track maintenance. This has to change because prolonged oversight of drainage systems maintenance can result in major problems, such as embankment or cutting slips and damages over the track structure. Despite this, it has been shown that measures to correct and adapt to this climate change have been taken in several countries. There are already several projects, which study possible adaptation measures and regulations as they are considering these imminent changes.

A new standardized design tool to improve drainage systems design and remediation works on existing drainage elements has been developed. It takes into account the effects of climate change and increase in this way the railway infrastructure resilience. It does introduce the effects of considering resilience KPI in the design process as well as the feedback provided by the continues analysis of the infrastructure.

Taking into account the problems, solutions and recommendations given in the article, the authors, intend to offer this study as a starting tool in the design, execution and modification of drainage design in railway systems. Therefore, this article aims to serve as a base tool for all work related to the world of drainage in railway infrastructures.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Acknowledgments

Authors would like to thank to Nerea Tarrago Garay from TECNALIA Research & Innovation for her help and support during the study.

References

- [1] D. Li, J. Hyslip, T. Sussman, S. Chrismer, *Railway Geotechnics* (2016).
- [2] A. Robinet, Les couches de forme traitées dans les structures d'assise ferroviaires, Mémoire Diplôme d'ingénieur Du Conserv. Natl. Des Arts Métiers. (2008).
- [3] N. Rail, *Route weather resilience and climate change adaptation plans: anglia, Netw Rail*. (2014).
- [4] L.S. J. Raja, M. Harding, N. Davies, M. Rouncefield, U. Roedig, J. Walden, O. Devan, A. Pages Maso, D. Sudell, *TrackWater: Supporting high-value, low-cost rail network drainage asset management*, in: *TrackWater Support. High-Value, Low-Cost Rail Netw. Drain. Asset Manag.*, Fourth International Conference on Railway Technology: Research, Development and Maintenance 3–7 September 2018 | Sitges, Barcelona, Spain, 2018.
- [5] P.E. Gautier, Slab track: review of existing systems and optimization potentials including very high speed, *Constr. Build. Mater.* 92 (2015) 9–15, <https://doi.org/10.1016/j.conbuildmat.2015.03.102>.
- [6] B. Lichtberger, *Manual de v[er]ia*, Eurailpress, DVV Media Group, 2011.
- [7] C. Esveld, *Modern Railway Track*, 2nd Ed., Delft Univ. Technol., 2001.
- [8] B. Indraratna, W. Salim, *Mechanics of Ballasted Rail Tracks: A Geotechnical Perspective*, CRC Press, 2005.
- [9] X. Han, E.T. Selig, Effects of fouling on ballast settlement, in: *Proc., 6th Int. Heavy Haul Railw. Conf.*, 1997: pp. 6–10.
- [10] J.G. Haynes, E.J. Yoder, Effect of repeated loading on gravel and crushed stone base course materials used in the AASHTO (American Association of State Highway Officials) Road Test, *Highw. Res. Rec.* 39 (1963).
- [11] P. Hornych, O. Hameury, J.L. Paut, Influence de l'eau sur le comportement mécanique des graves non traitées et sols supports de chaussées, in: *Symp. Int'l AIPCR Sur Le Drain. Des Chaussées*, 1998: pp. 249–257.
- [12] E.W. Lane, Progress report on studies on the design of stable channels by the Bureau of Reclamation, *Proc. Am. Soc. Civ. Eng.* (1953) 1–31.
- [13] R.D. Holtz, W.D. Kovacs, An introduction to geotechnical engineering, 1981.
- [14] J. Latvala, A. Nurmikolu, H. Luomala, Problems with railway track drainage in finland, *Proc. Eng.* 143 (2016) 1051–1058, <https://doi.org/10.1016/j.proeng.2016.06.098>.
- [15] C.F. Bonnett, *Practical Railway Engineering*, Imperial College Press, 2005.
- [16] K.R. Rushton, G. Ghataora, Understanding and modelling drainage of railway ballast, *Proc. Inst. Civ. Eng. – Transp.* 162 (2009) 227–236, <https://doi.org/10.1680/tran.2009.162.4.227>.
- [17] A. Nurmikolu, Degradation and frost susceptibility of crushed rock aggregates used in structural layers of railway track, 2005.
- [18] E.T. Selig, J.M. Waters, *Track geotechnology and substructure management*, Thomas Telford (1994).
- [19] A. Abeywickrama, Excess Pore Water Pressure Generation and Mud Pumping in Railways under Cyclic Loading, 2018.
- [20] T. Sussmann, M. Ruel, S. Chrismer, Source of ballast fouling and influence considerations for condition assessment criteria, *Transp. Res. Rec. J. Transp. Res. Board.* (2012) 87–94.
- [21] B. Indraratna, S.S. Nimbalkar, N. Tennakoon, The behaviour of ballasted track foundations: track drainage and geosynthetic reinforcement, *GeoFlorida 2010* (41095) (2010) 2378–2387, [https://doi.org/10.1061/41095\(365\)241](https://doi.org/10.1061/41095(365)241).
- [22] D. Ionescu, Ballast degradation and measurement of ballast fouling, *7th Railw. Eng. Proc.* 2 (2005) 12–18.
- [23] F. Feldman, D. Nissen, others, Alternative testing method for the measurement of ballast fouling: percentage void contamination, *CORE 2002 Cost Effic. Railw. through Eng.* 2002, 101.
- [24] E.T. Selig, B.K. Parsons, B.E. Cole, Drainage of railway ballast, in: *Proceeding 5th Int. Heavy Haul Railw. Conf. Beijing*, China, 1993.
- [25] C. Paiva, M. Ferreira, A. Ferreira, Ballast drainage in Brazilian railway infrastructures, *Constr. Build. Mater.* 92 (2015) 58–63, <https://doi.org/10.1016/j.conbuildmat.2014.06.006>.
- [26] B.K. Parsons, Hydraulic conductivity of railroad ballast and track substructure drainage, Department of Civil Engineering, University of Massachusetts, 1990.
- [27] Z. Su, H. Huang, G. Jing, Experimental analysis permeability characteristics of fouling railway ballast, *Metall. Min. Ind.* 7 (2015) 992–997.
- [28] C. Paper, The effect of ballast fouling on the hydraulic conductivity of the rail track, (2014). doi: 10.13140/2.1.4515.4242.
- [29] M. Koohmishi, M. Palassi, Effect of gradation of aggregate and size of fouling materials on hydraulic conductivity of sand-fouled railway ballast, *Constr. Build. Mater.* 167 (2018) 514–523, <https://doi.org/10.1016/j.conbuildmat.2018.02.040>.
- [30] S. Schmidt, S. Shah, M. Moaveni, B.J. Landry, E. Tutumluer, C. Basye, D. Li, Railway ballast permeability and cleaning considerations, *Transp. Res. Rec.* 2607 (2017) 24–32, <https://doi.org/10.3141/2607-05>.
- [31] T.V. Duong, V.N. Trinh, Y.J. Cui, A.M. Tang, N. Calon, Development of a large-scale infiltration column for studying the hydraulic conductivity of unsaturated fouled ballast, *Geotech. Test. J.* 36 (2013), <https://doi.org/10.1520/GTJ20120099>.
- [32] E.T. Selig, D.D. Cantrell, Track substructure maintenance—from theory to practice, in: *Proc., Am. Railw. Eng. Maintenance-of-w. Assoc. Annu. Conf.*, 2001.
- [33] F.J. Heyns, *Railway track drainage design techniques*, 2000.
- [34] T.W. Lambe, R.V. Whitman, *Soil Mechanics, Series in Soil Engineering*, Jhon Wiley Sons, 1969.
- [35] C. Kraemer Heilperno, J.M. Pardillo Mayora, S. Rocci Boccaleri, M. Romana Garc ía, V. Sánchez Blanco, M.A. Del Val Melús, *Ingenier ía de carreteras*, vol II, 2004.
- [36] E. Kuichling, The relation between the rainfall and the discharge of sewers in populous districts, *Trans. Am. Soc. Civ. Eng.* 20 (1889) 1–56.
- [37] PTSOM's Code of Practice, Volume 2 – Train System (CP2) "Drainage" CP TS 958, (n.d.).
- [38] N.A. Plataforma, Climatología, hidrología y drenaje, (2015) 1–25.
- [39] Ministerio de Obras Públicas y Urbanismo, Gobierno de España, Orden FOM/ 298/2016, de 15 de febrero, por la que se aprueba la norma 5.2 – IC drenaje superficial de la Instrucción de Carreteras., *Boletín Of. Del Estado*. (2016) 18882–19023. doi: BOE-A-2012-5403.
- [40] L.K. Sherman, The relation of hydrographs of runoff to size and character of drainage-basins, *Eos, Trans. Am. Geophys. Union.* 13 (1932) 332–339.
- [41] M.J. Lighthill, G.B. Whitham, On kinematic waves I. Flood movement in long rivers, *Proc. R. Soc. Lond. A* 229 (1955) 281–316.
- [42] . Issue, Track Drainage – Design and Construction RTS 3433, Access, 2006, pp. 1–36.
- [43] California high speed rail authority, California High-Speed Train Project Design Criteria, (2012) 1–1279.
- [44] R. Manning, J.P. Griffith, T.F. Pigot, L.F. Vernon-Harcourt, On the flow of water in open channels and pipes, 1890.
- [45] H.P.G. Darcy, Détermination des lois d'écoulement de l'eau à travers le sable, 1856.
- [46] G. Ghataora, K. Rushton, Movement of water through ballast and subballast for dual-line railway track, *Transp. Res. Rec. J. Transp. Res. Board.* 2289 (2012) 78–86, <https://doi.org/10.3141/2289-11>.
- [47] N.R.V. Renfe, 2-1-1-0 obras de tierra, *Drenajes y Saneam.* (1980).
- [48] I.U. of Railways (UIC), UIC 719: Earthworks and track bed for railway lines, 2008.
- [49] K.R. Rushton, G. Ghataora, Design for efficient drainage of railway track foundations, *Proc. ICE – Transp.* 167 (2012) 1–12, <https://doi.org/10.1680/tran.11.00023>.
- [50] H.R. Cedergren, *Seepage, Drainage, and Flow Nets*, John Wiley & Sons, 1997.
- [51] J.L. Sherard, L.P. Dunnigan, J.R. Talbot, Basic properties of sand and gravel filters, *J. Geotech. Eng.* 110 (1984) 684–700.
- [52] M. Foster, R. Fell, Assessing embankment dam filters that do not satisfy design criteria, *J. Geotech. Geoenvironm. Eng.* 127 (2001) 398–407.
- [53] R.K. Rowe, C.J.F.P. Jones, others, *Geosynthetics: innovative materials and rational design*, ISRM Int. Symp. (2000).
- [54] G.P. Raymond, Reinforced ballast behaviour subjected to repeated load, *Geotext. Geomembr.* 20 (2002) 39–61.
- [55] B. Indraratna, W. Salim, Deformation and degradation mechanics of recycled ballast stabilised with geosynthetics, *Soils Found.* 43 (2003) 35–46, https://doi.org/10.3208/sandf.43.4_35.
- [56] B. Indraratna, H. Khabbaz, W. Salim, D. Christie, Geotechnical properties of ballast and the role of geosynthetics in rail track stabilisation, *Proc. Inst. Civ. Eng. – Gr. Improv.* 10 (2006) 91–101, <https://doi.org/10.1680/grim.2006.10.3.91>.
- [57] B. Fatahi, H. Khabbaz, Enhancement of ballasted rail track performance using geosynthetics Adv. Pile Found., *Geosynth. Geoinvestigations Found. Fail. Anal. Repairs* (2011) 222–230, [https://doi.org/10.1061/47631\(410\)26](https://doi.org/10.1061/47631(410)26).
- [58] B. Indraratna, C. Rujikiatkarnjorn, S. Nimbalkar, Use of geosynthetics in railways including geocomposites and vertical drains, *Geo-Frontiers 2011* (2011) 4733–4742, [https://doi.org/10.1061/41165\(397\)484](https://doi.org/10.1061/41165(397)484).
- [59] B. Fatahi, H. Khabbaz, H.L. Ho, Effects of geotextiles on drainage performance of ballasted rail tracks, *Aust. Geomech.* 46 (2011) 91–102.
- [60] R.M. Koerner, *Designing with geosynthetics*, Xlibris Corporation, 2012.
- [61] N.A. Plataforma, Metodología para el diseño del trazado ferroviario, 2018.
- [62] Renfe, NRV 2-1-2-0 Obras De Tierra. Tratamiento De La Plataforma, 1982.
- [63] T.P. Division, MOD UK Railways Permanent Way Design and Maintenance Policy and Standards Issue 4, 2009.
- [64] G.E. Directorate, S. Organisation, Guidelines on Erosion Control and Drainage of, 2005.
- [65] I. Railways, P. Branch, *RAILWAY TRACKS DESIGN GUIDELINES FOR SPEEDS OF UP TO 250 KM/H Table of Contents*, 2013.
- [66] Highways Department Hong Kong, *Structures design Manual for Highway and Railways*, 2013.
- [67] *Railway Bureau, Technical regulatory standards on japanese railways*, Minist. Land Infrastruct. Transp. Tour. (2012) 424.
- [68] T.H.E. Kansas, C. Southern, the Kansas City Southern Railway Company Guidelines for the Design and Construction of Railroad Overpasses and Underpasses, (2008).
- [69] S.O.F. Florida, State of Florida Department of Transportation, (2012) 1–5.
- [70] H. Arisz, B.C. Burrell, Urban, drainage infrastructure planning and design considering climate change, in: *EIC Clim. Chang. Technol.* (2006) 1–9. IEEE.
- [71] European Environment Agency (EEA), Digest of EEA indicators 2014, 2014. doi: 10.2800/17963.
- [72] A. Prutsch, T. Grothmann, S. McCallum, I. Schauer, R. Swart, *Climate Change Adaptation Manual: Lessons learned from European and other industrialised countries*, Routledge, 2014.
- [73] C. Rachoy, KLWA: Anpassungsmassnahmen der ÖBB-Infrastruktur an den Klimawandel, in: *Work. "Neophyten Auf Bahnanlagen"*, Innsbruck, Austria, 2012.
- [74] B. Georgi, Network Rail, *Railway Drainage Systems Manual Issue 2, NR/L3/CIV/005 issue 2*, 2011, 2014.
- [75] Rail Safety and Standards Board (RSSB), Annual Safety Performance Report 2013/14, (2014) 254. <http://www.rssb.co.uk/Library/risk-analysis-and-safety-reporting/2014-07-aspr-2013-14-full-report.pdf>.